Award Number: W81XWH-07-1-0681

TITLE: Adjunctive Training and Support in the Application of Focused Assessment with Sonography for Trauma (FAST)

PRINCIPAL INVESTIGATOR: Howard M. Garon, Ph.D.
Shraga Rottem, M.D., D.Sc

CONTRACTING ORGANIZATION: Science Applications International Corporation
San Diego, CA 92121

REPORT DATE: July 2008

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01-Jul-2008	Final	17 Sep 2007 – 16 Jun 2008

4. TITLE AND SUBTITLE

Adjunctive Training and Support in the Application of Focused Assessment with Sonography for Trauma (FAST)

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-07-1-0681

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Howard M. Garon, Ph.D.
Shraga Rottem, M.D., D.Sc

E-Mail: howard.m.garon@saic.com

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Science Applications International Corporation
San Diego, CA 92121

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

We have developed and integrated all the key elements of a real-time interactive training visualization system, specifically for the task of training any designated personnel in successfully accomplishing a limited FAST examination. The interactive training visualization system consists of: (1) an easily transportable, almost ubiquitous ultrasound virtual phantom, (2) a means of estimating transducer relative position and motion when used adjunctively with the ultrasound machine and conjunctively with the ubiquitous phantom, (3) a volumetric image database for each search quadrant and (4) a syllabus to direct the training.

15. SUBJECT TERMS
Medical training, FAST, trauma

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			USAMRMC
U	U	U	UU	15	19b. TELEPHONE NUMBER *(include area code)*

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Introduction

Focused Assessment with Sonography for Trauma (FAST) has assumed an important role in the emergency room (E/R) whenever blunt abdominal trauma is indicated. That role has since expanded outside the E/R with the introduction of relatively low-cost and ultra-portable color ultrasound machines [1]-[4]. The ease of operation of these newer machines along with the limited examination requirements of a FAST could permit emergency response personnel of all classes and educational levels to participate in trauma assessment. The wider implication is that in times where the conventional emergency response system is overwhelmed or simply not present, such as on the battlefield, in a civil disaster or aboard a deployed SSBN, application of a FAST by trained personnel could be effective and could save lives. More so than any other imaging modality, U/S is unique in that the success of a scan and a corresponding diagnosis is completely dependent upon the skill of the operator. To offset this very basic requirement there have been attempts to utilize wideband remote links [5]. In the absence of a broadband link that approach obviously becomes untenable. Moreover, that approach still doesn't satisfy the fundamental problem of being able to train and assist the operator in actually conducting a FAST. Providing a consistent schema for training as well as diagnosis assist, a schema that could be distributed throughout the services, then serves as the basis for this study.

Anticipating a general need for supplying a capability of this type, Intellison in conjunction with Science Applications International Corporation (SAIC) had already developed a fairly comprehensive set of core components and expert-base. Both the core components and the expert-base were, however, directed at whole-body emergency response imaging[6]. Nonetheless, they did allow us to recognize the necessary ingredients in constructing a successful training program. First and foremost we recognized that initially limiting the scope of the training was most important at the outset. Once the basics were in place we felt we could always progress to providing training in more advanced (and necessarily more complicated) techniques with a greater sense of confidence. There are many extensions to FAST that are practiced in the E/R. We purposely chose as a first step to implement a limited FAST protocol trainer, limited in the sense that only an intra-peritoneal free fluid search would be the objective. The trainee would only have to have a background in basic anatomy as a preliminary requirement. At completion of training we would expect all personnel at all incoming skill levels to achieve limited FAST protocol competency with sensitivity and specificity comparable to that of an experienced professional.

Body

Our (SAIC and Intellison) joint goal is to demonstrate feasibility to the US Army the ability to train and assist any designated personnel in performing a limited FAST protocol with sensitivity and specificity comparable to that of an experienced ultrasonographer. Although many different and extended variants of FAST are practiced, we will purposely restrict the FAST to a free intra-peritoneal fluid search within each of the four quadrants viz., left and right upper quadrant (LUQ and RUQ, respectively), pericardial, and pelvic. The statement of work for this study delineates four distinct tasks for accomplishing this goal:

(1) Development of an interactive training visualization system,
(2) Delineating the taxonomy of handheld ultrasound (U/S) scanner motions,
(3) Establishing a training syllabus, and
(4) Building a library of appropriately sampled U/S images.

We will discuss each one of these tasks in turn.

Task 1. Development of an interactive training visualization system

The focus of our first effort under this award was to develop an interactive training visualization system or simulator. The simulator, based upon adjunctive deployment of a real ultrasound machine with handheld transducer, would serve as the primary training vehicle. We wanted all trainees to become familiar with the actual ultrasound machine they would operate in the field and simultaneously provide them with a means of refreshing their skills. The simulator we had in mind was to be unique in that it would rely upon two key elements: (1) an easily transportable, almost ubiquitous ultrasound phantom and (2), a means of estimating transducer relative position and motion when used adjunctively with the ultrasound machine and conjunctively with the ubiquitous phantom. Although the effort itself turned out to be far more tedious than we could have anticipated, we believe the final outcome was worth that effort. We consider the interactive training visualization system as developed under this grant to represent a genuine advance.

The major difficulty in deriving the key elements of the interactive system, the phantom and the transducer motion estimator, was due precisely to their interlocked development. In other words, a physical change in the construction of the phantom would directly impact the success of any motion estimator. After many trials (we will not detail those here) we arrived at a combination that demonstrates the level of consistency we require for training. At the same time the system is relatively easy to construct and should be able to run in real time (at frame rate) embedded within almost any modern ultrasound machine.

The first virtual phantom we constructed consisted of a 3 cm thick (silicon rubberbase GI-1000) rectangular mat (figure 1a). To increase softness and ensure a smooth surface, the silicon rubberbase was combined with a RTV diluent at slightly better than 10% prior to pouring in the mold. Embedded within the silicon (and also placed in the mold prior to pouring) was a non-uniform rectangular grid mesh made out of 0.5 mm thick by 6.3 mm high aluminum (figure 1b). However, even though the mat was only 3 cm thick, the GI-1000 silicon proved to have far too great a loss for a relatively low frequency (3 MHz)

ultrasound. We subsequently discarded our first candidate. A search for a comparatively low loss plastic useful at ultrasonic frequencies suggested that the phantom could instead be constructed out of styrene. For the feasibility demonstration we chose to modify a commercially available styrene container (figures 2a) with dimensions 7.5 cm (W) x 12.5 cm (L) x 5 cm (H). Another mesh (figure 2b) was constructed by first folding then expanding a thin (3mm) aluminum sheet so that the sheet appeared with crunulations on the order of 1 cm high. Small holes were placed on the crest of the crunulations uniformly across the sheet by just cutting the sheet on one side. The mesh was glued to the bottom of the container and the container filled with water. The result was simple but effective. The transducer could be placed almost anywhere on the surface of the container with a very strong image of the mesh with multiple reverberations.

To determine motion of the transducer in the horizontal (top surface of the container) the companion motion estimation algorithm was then based upon a spatial block template approach. This approach is a commonly deployed technique used to detect motion within a sequence of images. In our case we chose a spatial block 16 pixels square in a designated reference frame (usually the first acquired frame). The selection was accomplished by first resolving the portion of the angular aperture with the most energy, then limiting that aperture spatially by the depth of the aluminum grid. This special block then serves as the basic block for doing a 2D crosscorrelation over succeeding frames within all physically realizable lags and advances. Selecting the greatest crosscorrelation coefficient value gives the actual 2D lag (or advance) of the reference block to the next frame in sequence. In this manner we could calculate any motion in x and y including rotation of the transducer about an axis normal to the surface of the container. While absolute horizontal transducer position could also be calculated[7], we decided that for our limited purposes here we only required relative motion. In practice once a transducer was placed on a subject, the trainee would not look directly at the motion of their hand. Instead, they would (and should) focus on just the ultrasound image on the screen of the machine.

Probably the easiest motion to calculate was the tilting of the transducer about the maximum response axis, either laterally or axially When the transducer is tilted laterally, the image of the grid with its reverberations will tilt directly with the transducer. The transducer aperture is rectangular so the energy of the transducer should be deposited with a gaussian distribution centered at the lateral angle of tilt. The amount of energy deposited (width of the gaussian) will in turn be determined by how well the transducer couples to the phantom. Since the surface of the transducer is rigid, maximum energy (maximum gaussian width) is coupled to the phantom when the face (the surface) of the transducer squarely meets with the surface of the container. Tilting the face of the transducer away from the container surface will decrease coupling. This is readily and consistently quantifiable for any transducer.

To illustrate all this, we have included with this report several .avi clips demonstrating, respectively, transducer motion in the horizontal plane, transducer tilt in both lateral and axial angle on the top surface of the virtual phantom.

Task 2. Taxonomy of handheld ultrasound (U/S) scanner motions

As depicted in figure 3, the motion of a handheld transducer can be completely described using the general motions sweep, tilt and rotate[8]. This second task then was to place

these motions into context by delineating a taxonomy of preferred sequence of these general motions for conducting a free intra-peritoneal fluid search in each of the four quadrants. Once a taxonomy had been defined then these same motions would naturally form the basis of the training syllabus. In providing the ultrasound movie clips for our fourth task， Dr. Beatrice Hoffmann [9] depicted pictorially all the hand motions she employed almost on a frame-by-frame basis (see figure 4a for an example). We were able to take these pictorials and quantify her actions (e.g., Table 1). The result was the taxonomy of motions we were hoping to obtain along with particular strategies (transducer movements) for each quadrant search. In almost all instances we noted that once the transducer was placed into position on a subject for a given quadrant search the transducer was kept in position, obviating any substantial changes in the horizontal plane[10]. Generally, the transducer was either tilted or rotated to avoid a rib in both the RUQ and LUQ quadrants, to look just below the rib cage for the subxiphoid (cardiac) view and to look over the symphysis at the bladder.

Task 3. Training syllabus

A proposed syllabus for training personnel in conducting a limited FAST is provided in the Appendix. While the syllabus follows the recommendations and guidelines[11] as set forth jointly by the American Institute of Ultrasound In Medicine (AIUM) and the American College of Emergency Physicians (ACEP), it also couples in the transducer motion taxonomy derived under the previous task and the intended flexibility of the interactive visualization system. The interactive visual system allows action repetition which is instrumental to learning. The system also allows the trainee to move almost frame-by-frame, both forward and backward, to capture key elements of each ultrasound image. This allows the operator to more fully understand each ultrasound image. A critical portion of the syllabus is also directed towards what happens when the operator is improperly handling the transducer. With the interactive visual system the operator can experiment and be coached as to how to reorient the transducer and regain a proper image.

Task 4. Library of appropriately sampled U/S images

The last task is actually the final image realization supporting tasks 2 and 3. This equates to the construction of a volumetric image database where the individual images can be in any format that lends itself towards retrieval then in implementing a sequential real-time display of those images. While there are a number of raw image formats that could lend themselves towards construction of a virtual visualization system, we chose the most expedient - a simple bitmap construction. While this format does not minimize the storage required (in fact, it's quite the opposite) bitmaps are among the easiest to index and retrieve frame-by-frame for the real-time display. We would however expect that future efforts would maintain and store the raw images in the Digital Imaging Communication in Medicine (DICOM) format, especially since that format has almost universal acceptance in medical image exchange[12] and has begun to dominate as a standard output format from most imaging instruments..

Dr. Beatrice Hoffmann[9] initially captured and transferred four FAST cases in MP4 format. Two of those cases were positive for free fluid while two were negative. Following both HIPPA and US Army Human Experimentation regulatory requirements,

the MP4 clips were stripped of all subject identifiers prior to transfer to SAIC. At SAIC the MP4 videos were deconstructed into their separate and distinct bitmap frame constituents using ImageJ[13]. As discussed above, separate and distinct bitmap images anticipate our requirement to build a volumetric bitmap database. Every frame of the clips were related to transducer motion and characterized as to approximate transducer rotation and tilt (task 2). As required in reconstruction, the volumetric database is accessed according to calculated trainee transducer movements over the phantom (task 1), in turn generating a sequence of images to be viewed by the trainee. The only remaining technical hurdle was how to intercept the video data stream internal to the ultrasound instrument and replace that data stream with the derived (virtual) sequence of images. We were able to resolve that problem by obtaining from Terason a Software Development Kit (SDK) that allowed us internal access to the video data stream on any of the Terason ultrasound devices. Using the SDK and Microsoft Visual Studio we were able to build the appropriate software in C++. That software successfully funnels the video as seen by the transducer to our motion estimation system and selects the appropriate image from the database on the basis of the motion calculation. This is accomplished at full frame rate[14].

Conclusions

We have developed and integrated all the key elements of a real-time interactive training visualization system, specifically for the task of training any designated personnel in successfully accomplishing a limited FAST examination. The interactive training visualization system consists of: (1) an easily transportable, almost ubiquitous ultrasound virtual phantom, (2) a means of estimating transducer relative position and motion when used adjunctively with the ultrasound machine and conjunctively with the ubiquitous phantom, (3) a volumetric image database for each search quadrant and (4) a syllabus to direct the training.

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[6] S Rottem and L Young : AI in Medical Imaging (Diagnostic Ultrasound) Presentation to USNMD, Balboa, August 19,2003.
[7] Absolute horizontal position could be calculated by noting in any acquired image the specific grid horizontal dimensions (distance between crunulations) at that point. Since the folded mesh is non-uniform, those dimensions will be unique from the perspective of each and every point on the surface of the grid. Mapping those unique dimensions to a previously stored look-up table would then give the absolute location on the horizontal surface of the grid.
[8] C Wick and S Pieper, "Constraint-Based Navigation in Three-Dimensional Scenes", ERCIM News No.46, July 2001.
[9] Beatrice Hoffmann, MD, PhD, RDMS and Ultrasound Director of the Johns Hopkins University Emergency Medicine department, Baltimore, MD.
[10] For our purposes, the horizontal plane is defined as the plane tangent (parallel) to the surface of the transducer face at the transducer midpoint.
[11] *AIUM Practice Guideline for the Performance of the Focused Assessment With Sonography for Trauma (FAST) Examination*, American Institute of Ultrasound In Medicine (AIUM), Laurel, MD, October 2007.
[12] http://www.hipaafaq.com/hisb_dicom.htm
[13] An extremely comprehensive and powerful Java program available as free source and executables from http://rsbweb.nih.gov/ij/ , courtesy of NIH and Wayne Rasband.
[14] Frame rate may vary between 15 to 30 frames per second between various ultrasound systems.

<u>Appendix:</u> Teaching the FAST protocol to HM-8404 Field Medical Service Technicians

Each trainee will have access to a SAIC/Intellison FAST simulator on their own ultrasound machine.

Procedure 1: FAST - Detect free fluid using ultrasound

a. Why?
    i. What is free fluid?
        - Blood, urine, bile
    ii. Indicator of damage
        - Organ, vascular, lymphatic
    iii. Application to blunt trauma
        - Multiple casualties (Triage)
        - Evacuation timing
        - Prep/heads-up for secondary care
b. How does an ultrasound machine see?
    i. Optical analog using a flashlight. – Examples of optically reflecting/transparent materials
    ii. Ultrasound equivalence - Echogenic/anechoic = white/black
    iii. Effect of transducer orientation
c. How does free fluid appear on an ultrasound image?
    i. Relatively easy to see on image – anechoic = jet black
    ii. Examples (shows contrast between free fluid and everything else)

Procedure 2 - Right Upper Quadrant Search (Perihepatic/Right Flank or Morison Pouch View). Liver is used an "ultrasound window" to search the immediate region of the liver as well as the surrounding (hepatorenal/ Morison pouch) space for free fluid:

a. Placement of transducer
b. Transducer movements required to accomplish search
    i. Slight superior angulation of the transducer allows imaging of the right pleural space for free fluid.
    ii. Inferior angulation of the transducer allows visualization of the inferior pole of the right kidney as well as the right paracolic gutter.
c. Key features of normal views (examples of negatives)
d. Most frequently occurring sites (examples of positives)

Procedure 3 - Left Upper Quadrant View (Perisplenic/Left Flank) Use the spleen as a window to view the region of the spleen and the (perisplenic) space above the spleen, below the diaphragm, and above the left kidney:

a. Placement of transducer

b. Transducer movements required to accomplish search
    i. Angulation superiorly to search left pleural space.
    ii. Inferior angulation to search above the left kidney or in the left paracolic gutter.
c. Key features of normal views (examples of negatives)
d. Most frequently occurring sites (examples of positives)

Procedure 4 (Most difficult) - Pelvic View (Retrovesical, Retrouterine, or Pouch of Douglas). Search the lower portion of the peritoneum:

a. Placement of transducer
b. Transducer movements required to accomplish search
c. Most frequently occurring site is superior and posterior to the bladder and uterus (examples of positives).
    - Increased difficulty associated with searching through partially-filled bladder

Procedure 5 - Pericardial View (Subcostal/Subxiphoid). Left lobe of liver serves as key to searching region surrounding the heart, particularly its right side:

a. Placement of transducer
    i. Sagittal plane
    ii. transverse (4-chamber) plane
b. Transducer movements required to accomplish search
    i. Rocking allows search of the inferior vena cava and hepatic veins
c. Key features of normal views (examples of negatives)
d. Most frequently occurs (examples of positives) within the anterior or posterior pericardium.

Procedure 6 – Practice. Repetition of Procedures 2 through 5 with increasing levels of pathological complexity.

Procedure 7 – Instructor personal review. Repetition of Procedures 2 through 5 with random introduction of pathology and with direct instructor oversight.

Procedure 8 – Certification of acquired skills.

Figure 1a. 3cm thick rectangular slab constructed using GI-1000 RTV and diluent.

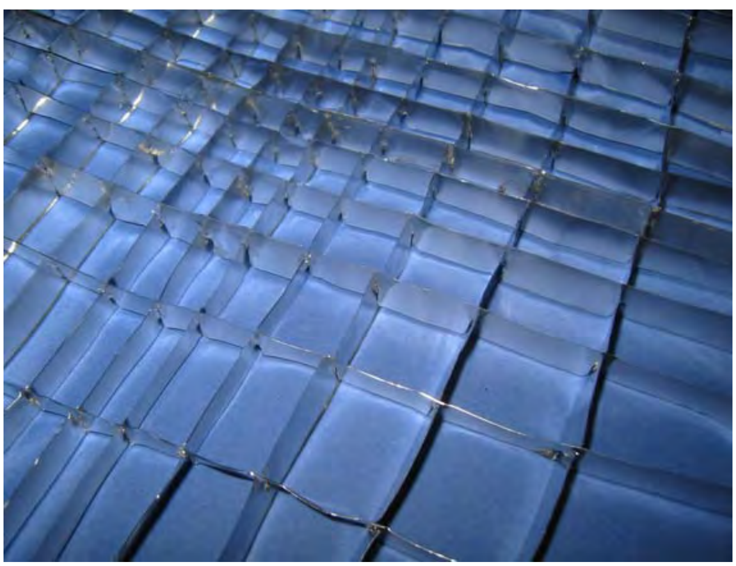

Figure 1b. 0.5 cm high, non-uniform aluminum mesh embedded within slab of figure 1a.

Figure 2a. Styrene container with folded aluminum mesh.

Figure 2b. Closeup of aluminum mesh.

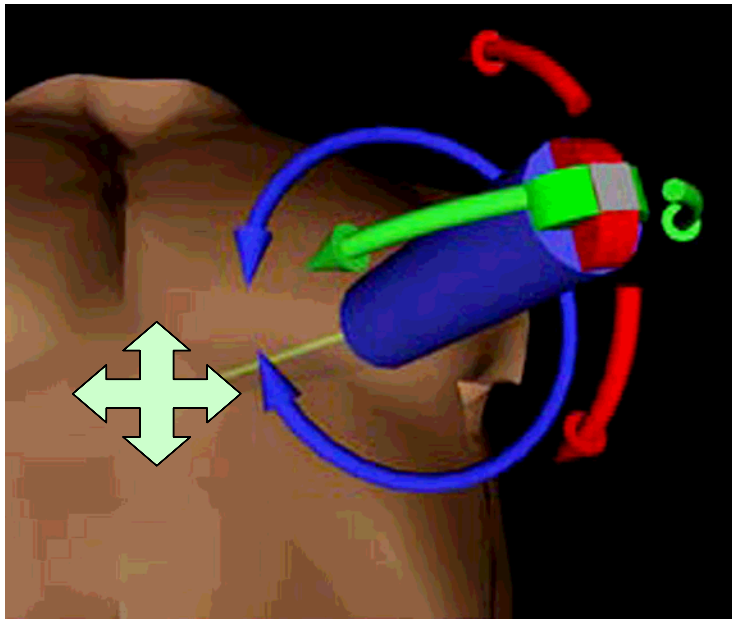

Figure 3. Transducer motion – sweep, rotate and tilt. (Figure is modified from ref [8]).

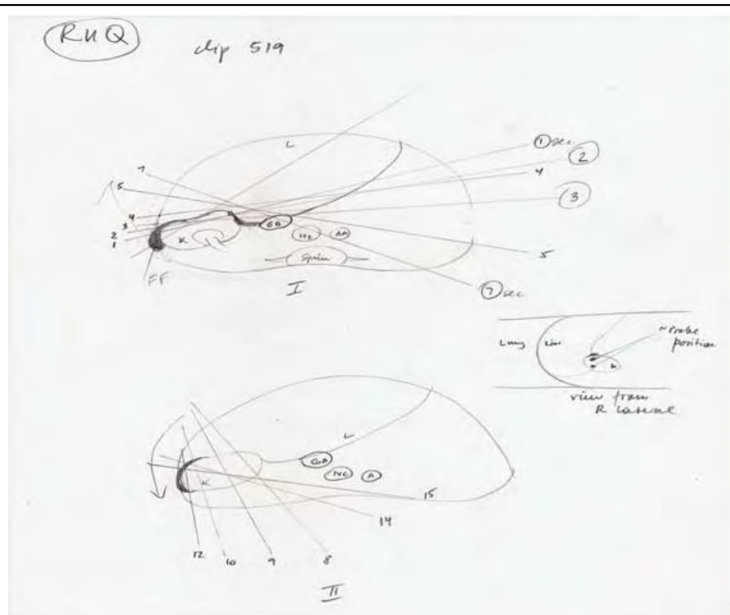

Figure 4. Reconstruction of transducer movement from one MP4 clip for RUQ quadrant search.

Frame	Action Set	dX	dY	Lateral angle	Axial angle
000	000	480	294	+20.12	+00.00
015	000	512	300	+14.63	+00.00
030	000	510	346	+05.92	+00.00
045	000	489	298	+10.24	+00.00
060	000	476	373	-13.43	+00.00
075	000	461	387	-20.61	+00.00
090	000	445	400	-27.79	+00.00
105	001	229	300	-59.45	+00.00
120	001	176	303	-69.95	+00.00
135	001	124	328	-77.86	+00.00
150	001	111	296	-80.51	+00.00
165	001	098	265	-83.16	+00.00
180	001	170	290	-53.42	+00.00
195	002	242	315	-23.68	+00.00
210	002	271	302	-11.29	+00.00
225	002	271	302	-11.29	+00.00

Table 1. Quantification of figure 4.